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ASD-TDR-63-569

APPLIED RESEARCH OF BEAM INTERACTION STRUCTURES FOR TRAVELING WAVE TUBES

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-569

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Electronic Technology Laboratory
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Project 4156, Task 415603

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NOTICES

FOREWORD

This report was prepared by the General Electric Company, Traveling Wave Tube Produce Section, Palo Alto, California, on Air Force contract AF33(657)-8360, under Task No. 41533 of Project No. 415603, "Applied Research of Beam Interaction Structures for Traveling Wave Tubes." The work was administered under the direction of Electronic Technology Laboratory (now designated Electronic Technology Division of AF Avionics Laboratory), Aeronautical Systems Division. Robert L. Harris was project engineer for the Laboratory.

The research covered by this report began in April 1962, and was concluded in April 1963. R. M. White and C. E. Enderby were project engineers for the General Electric Company. They gratefully acknowledge the assistance of C. K. Birdsall of the Department of Electrical Engineering, University of California, Berkeley.

This is the second Technical Documentary Report prepared under this contract. (The first, ASD-TDR-63-224, published in March 1963, is entitled "Properties of Ring-Plane Slow-Wave Circuits.") This final report has been designated TIS-R63ELM-233-5 in the General Electric Company Technical Information Series.

ABSTRACT

This report summarizes the results of the study program, and gives the experimental results of the tube built with one of these circuits. A comprehensive discussion of the study program is given in Technical Documentary Report No. ASD-TDR-63-224, entitled "Properties of Ring-Plane Slow-Wave Circuits".

The experimental tube was built such that both modes that can exist on a circuit were coupled independently through separate waveguides, to allow testing of each mode. The tube was tested with both a hollow beam and a solid beam. The tube gave 20 db gain in the ++ mode and about 3 db gain in the +- mode. The power obtained in the ++ mode was about 15 kw with the hollow beam and about 8 kw with the solid beam. The perveance was slightly different for the two beams, so both of these represent about 0. 5 kw maximum and the hollow beam produced 4 kw maximum. Here the difference is mainly due to the radial variation of the field. The power measurements were made by feeding back part of the output power to the input, since this tube is basically an amplifier.

The conclusions that can be reached from this program are that the ring plane circuits are very well suited to the high-frequency high-power region as both an oscillator and an amplifier. They can have high gains and high efficiencies with large peak power and average power capabilities.

PUBLICATION REVIEW

This program presents the significant findings of an Air Force sponsored program. It does not direct any specific application thereof. The report is approved for publication to achieve an exchange and stimulation of ideas.

FOR THE COMMANDER:

CONTENTS

ILLUSTRATIONS

DEFINITION OF SYMBOLS

A_i	radius of barrel
a_i	inner diameter of rings
a_o	outer diameter of rings
c	velocity of light
D	diameter of barrel
E_z	axial electric field intensity
f	frequency
I_o	modified Bessel function of first kind
K	axial field interaction impedance
K_o	modified Bessel function of second kind
k	ω/c
L	radial length of slot in plane
m	axial spatial harmonic number
n	azimuthal spatial harmonic number
p	circuit pitch
T	thickness of plane
t	radial thickness of rings
v_g	group velocity $\left(\frac{\partial\omega}{\partial\beta}\right)$
v_p	phase velocity $\left(\frac{\omega}{\beta}\right)$
w	axial width of slot in plane
β	phase constant
γ	propagation constant $\left(\gamma^2 = k^2 - \beta^2\right)$
δ	axial thickness of rings
ϵ_o	permittivity of free space $\left(8.854 \times 10^{-12} \text{ joule/meter}\right)$
η_o	characteristic impedance of free space $\left(377\,\Omega\right)$
λ	wavelength $\left(\frac{2\pi}{\beta}\right)$
μ_o	permeability of free space $\left(4\pi \times 10^{-7} \text{ henry/meter}\right)$
ω	radian frequency $(2\pi f)$

INTRODUCTION

This report summarizes the program of applied research on a TWT interaction structure for high-power and high-frequency applications. The structure is of the ring-plane family, and consists of periodically spaced rings mounted on radial planes. An example is shown in Fig. 1. The program consisted basically of two parts. The first part was a fairly exhaustive study of the properties of this family of circuits, including such items as propagation characteristics, mode suppression, interaction impedance, bandwidths, field variation, etc. The second part consisted of building a traveling-wave amplifier in the 35 Gc region using one of these circuits, and testing of this amplifier.

The reasons for choosing the ring-plane family to operate in the high-frequency, high-power region are as follows:

1. The beam interaction space within the rings is large by comparison with other slow-wave circuits. The circumference is approximately the free space wavelength, which makes it possible to put large beam currents through the circuit to obtain high output powers and efficiency.
2. The rings, which in high-power applications are the hottest part of the circuit, are directly connected to substantial radial planes, which provide good thermal conductivity and means for cooling the rings.
3. The impedance of the structure is high, indicating strong interaction within a beam to obtain high gains and high efficiencies.
4. The structure is fairly easy to fabricate, due to its simple geometry and large size.

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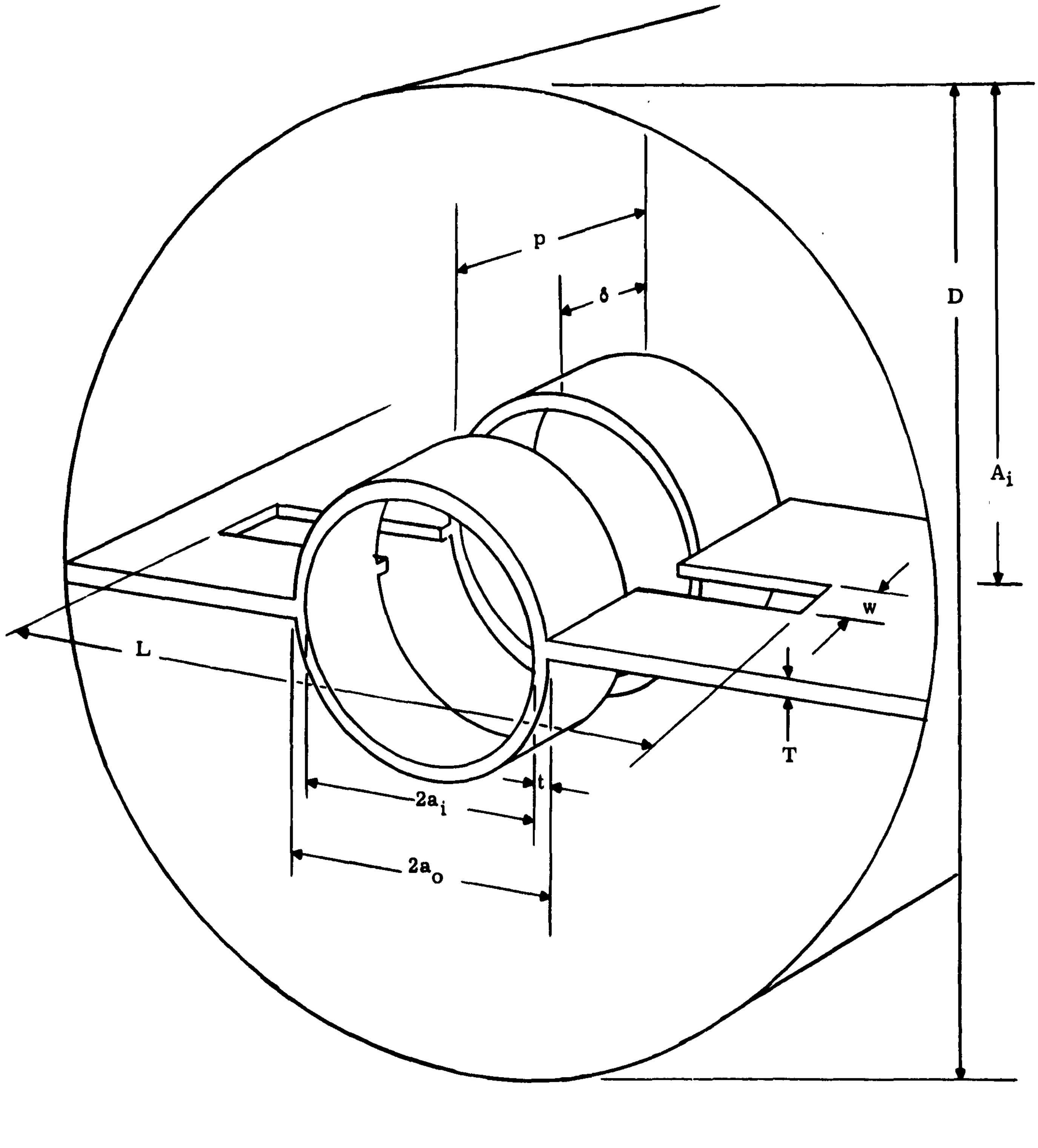


Fig. 1. A ring-plane circuit showing symbols used to denote circuit dimensions.

CIRCUIT PROPERTIES

Properties of ring-plane slow-wave circuits were extensively investigated during the course of this program, and that work was reported in detail in ASD-TDR-63-224 (TIS R63ELM233-4). A brief summary of the circuit is given in the following paragraphs.

A particular circuit was chosen as a prototype to be studied in this phase of the program. Variations were made on this central circuit, and the influence of these variations on the electrical properties was investigated. The prototype circuit has two planes, and dimensional ratios as:

$$\frac{\delta}{p} = 0.5, \quad \frac{a_i}{p} = 0.796, \quad \frac{a_o}{p} = 0.995, \quad \frac{t}{p} = 0.199, \quad \frac{T}{p} = 0.199.$$

One may consider that the circuit is composed of two ladder circuits in parallel. Two modes are then found for which these two halves are excited, either in phase or out of phase. The in-phase or ++ mode has the longitudinal electric field in phase on both halves, and thereby has a finite longitudinal electric field on axis. The out-of-phase or +- mode has a longitudinal electric field and is out of phase two halves as zero electric field on the axis. Therefore the ++ mode is the one that is normally of interest to interact with an electron beam. However, with any beam of any finite radial extent, care must be taken not to excite the +- mode. When the two-plane circuit is enclosed in a conducting barrel, both modes cut on at a frequency near the cuton frequency for the TE_{11} coaxial mode and propagate up to an upper cutoff near $ka = 1$. This is shown in the propagation characteristics in Fig. 2. In this case there is no barrel, so there is no lower cutoff.

The current associated with the +- mode flows on the internal circumference of each of the rings, and is the normal ring mode. For the ++ mode the current flows on the internal circumference of the ring toward the planes and then down the edge of the plane. Bisecting this circuit through the planes will not interpret the current flow for the ++ mode but will interpret the current flow on the +- mode, which then allows mode suppression of the +- mode with little effect on the ++ mode. This can be accomplished by inserting a lossy material between the bifurcated circuits, through which the current of the +- mode must flow.

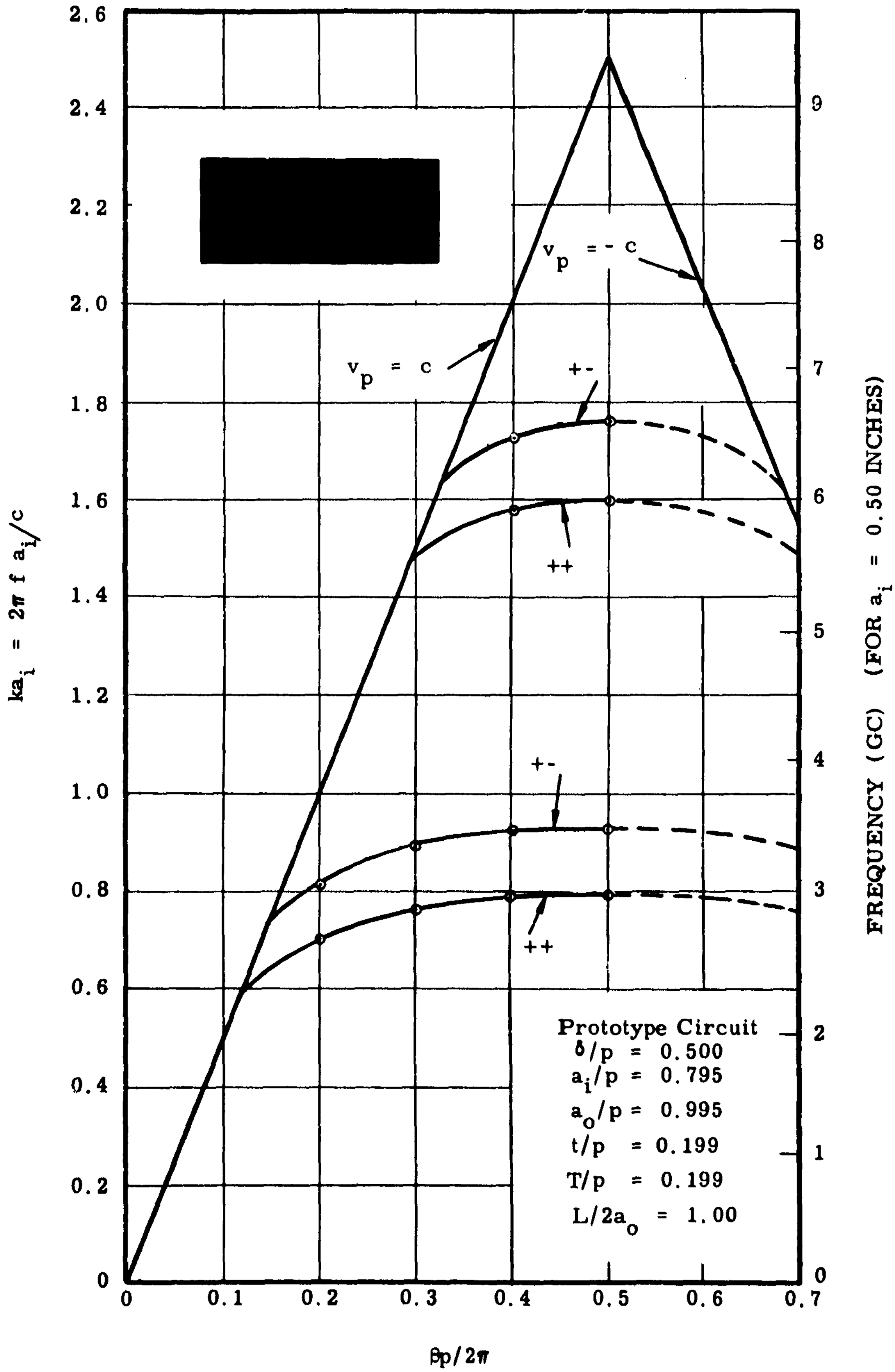


Fig. 2. Propagation characteristics of prototype circuit. The frequency scale on the right shows actual frequencies for a circuit with ring ID of one inch. The ++ and +- modes were identified as such from perturbation measurements. Backward-wave components are shown dashed; (they are mirror images about the $\beta p/2\pi$ = 1/2 point of the fundamental components).

The axial electric field varies with both the radial and azimuthal coordinates, r and θ. The functional dependences were determined by starting from a Fourier analysis of the axial electrical field measured at the rings of the prototype circuit. Fig. 3 shows the axial electric field at the inside of the prototype (and other circuits) measured as a function of θ; the points were obtained by perturbing the fields and the rings with a 0.070-inch-diameter sapphire rod (extending over the length of the circuit) and moving the rod in the θ direction. The axial electric field amplitude appears to approximate a $\sin\theta$ distribution at the two frequencies for which measurements were made. This variation is, of course, the same as that of a plane ladder. For the ++ mode the E_z field is proportional to $|\sin\theta|$. With this information, we write this electric field in terms of the axial and azimuthal spatial harmonics, $r < a_i$, as

$$E_z(r, \theta, z) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} A_{m,n} I_n(\gamma_m r) \cos(n\theta) \exp j\left(\omega t - \beta_o z - \frac{2\pi m z}{p}\right) \qquad (1)$$

At the rings $(r = a)$, from experiment, the $m = 0$ field behaves as

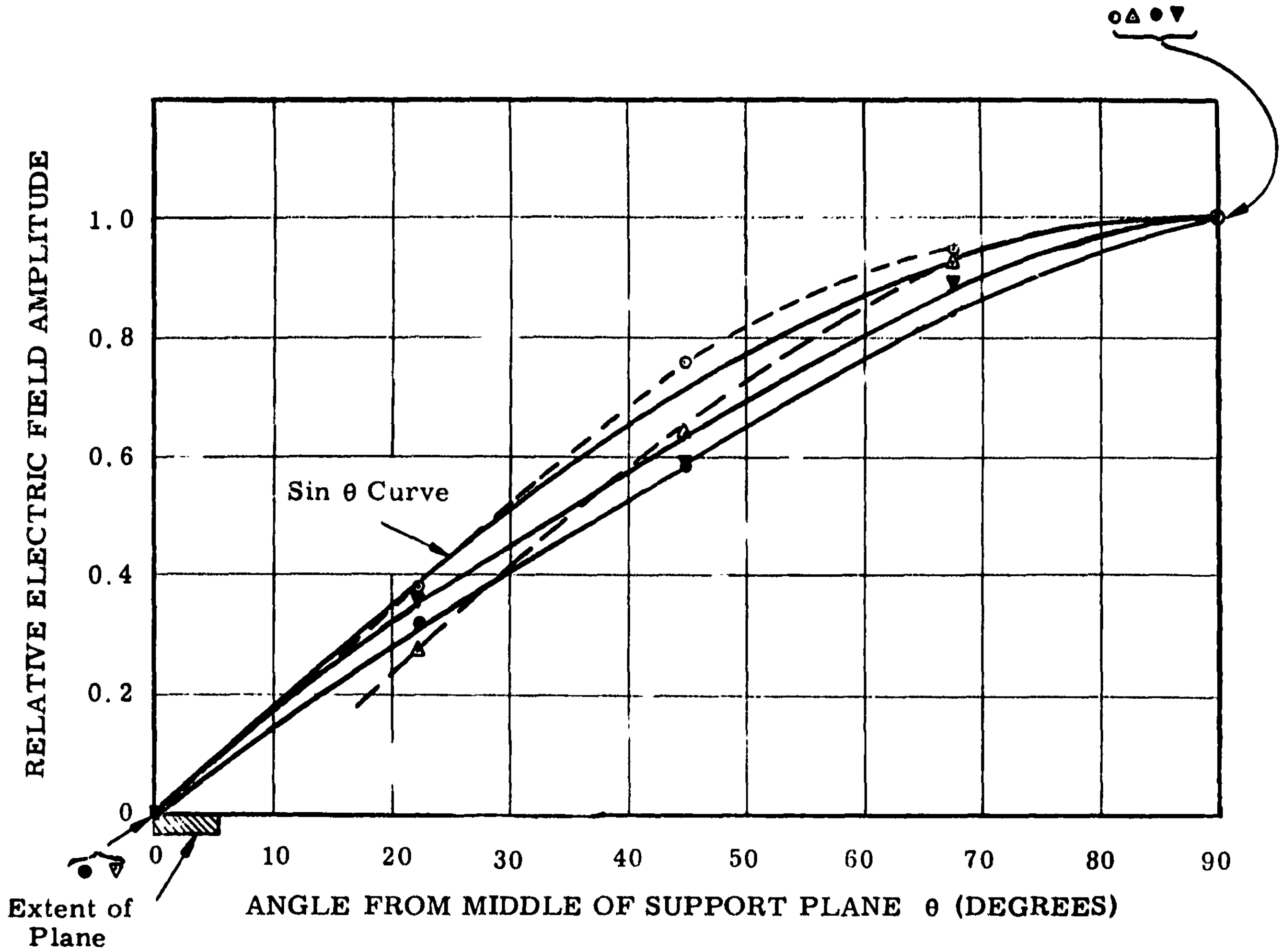
$$E_{zo}(a, \theta) = E_{zo}\left(a, \frac{\pi}{2}\right) |\sin\theta| \qquad (2)$$

We require that the expansion (1) match the experimental data (2) at $r = a$. Ignoring the axial spatial harmonics, the fundamental relative amplitudes in θ (the $A_{o,n}$) are readily obtained by equating the Fourier cosine series to $|\sin\theta|$. The result is

$$E_{zo}(a, \theta) = \left(\frac{2}{\pi}\right) E_{zo}\left(a, \frac{\pi}{2}\right) \left[1 - \left(\frac{2}{3}\right)\cos 2\theta - \left(\frac{2}{15}\right)\cos 4\theta \cdots - \left(\frac{2}{4n^2 - 1}\right)\cos 2n\theta \cdots\right] \qquad (3)$$

In the usual manner, these fields are continued inward and outward, so for $r < a_i$

$$E_{zo}(r, \theta) = \left(\frac{2}{\pi}\right) E_{zo}\left(a, \frac{\pi}{2}\right) \left[\frac{I_o(\gamma_o r)}{I_o(\gamma_o a)} - \frac{2}{3}\frac{I_2(\gamma_o r)}{I_2(\gamma_o a)}\cos 2\theta - \frac{2}{15}\frac{I_4(\gamma_o r)}{I_4(\gamma_o a)}\cos 4\theta \cdots\right] \qquad (4)$$



T/p = 0.199 ○ (++) γa = 0.71 } δ/p = 0.148, T/p = 0.199
△ (++) γa = 1.83

● (+-) γa = 0.58 } δ/p = 0.500, T/p = 0.199 (Prototype)
▼ (+-) γa = 1.20

Fig. 3. Electric field measured as a function of angle around the inside of the rings ($r = a_i$) for several ring-plane circuits. Dimensions not listed are the same as the prototype.

This expression gives the functional dependence of E_z on r and θ, which can be checked by further perturbation measurements for $r < a_i$. The measured and calculated radial variations of axial field are plotted in Fig. 4. The calculated curve plotted in Fig. 4 used only the first three terms of the series ($n = 0, 1, 2$); also shown there are the sums at $r/a = 1$ for series terms from $n = 0$ (angle-independent term) through $n = 5$ and for $n = \infty$. Note that the series appears to be converging slowly to the $\theta = 0^{\circ}$ curve, but that the sum for $\theta = 90^{\circ}$ is converging to a value about 10 per cent below the measured value. This discrepancy may be due to the perturbation of transverse field by the sapphire rod used in the measurements. The presence of E_r will raise the effective perturbation. The perturbing rod is long and thin (so as to "see" only E_z); but the experimentally determined ratio of transverse to axial polarizability of the rod is not negligible, being approximately one-fifth (as determined in a uniform waveguide); this suggests that the transverse field amplitude at the rings may be as much as about 1.2 times the longitudinal field amplitude at $r = a$, (after some algebra).

The axial field interaction impedance $\left(K \equiv E_z^2 / 2\beta^2 P\right)$ at the rings and along the circuit axis is plotted in Fig. 5. The impedance has not been corrected for the existence of axial spatial harmonics other than the fundamental, nor for radial fields. On the axis the axial spatial harmonics, $m > 0$, are taken to be negligible; at the rings, ignoring the $m > 0$ harmonics, an error in E_z of perhaps 10 per cent comes in due to the E_r fields, as discussed in the previous paragraph. K thus refers to E_z^2 total, with no breakdown into axial harmonics; however, the $m = 0$ fundamental will be dominant in almost all of the measurements to follow. The maximum γa_i for this mode (the value of γa_i at the cutoff resonance frequency) is indicated along the horizontal axis in Fig. 5 as $(\gamma a_i)_{res}$.

The change of impedance with γa_i can be thought of as resulting from two effects: (1) the increasing concentration of fields near the rings as γa increases, and (2) the decrease in group velocity with increasing frequency. The general character of K with γa can be compared with that of an ideal

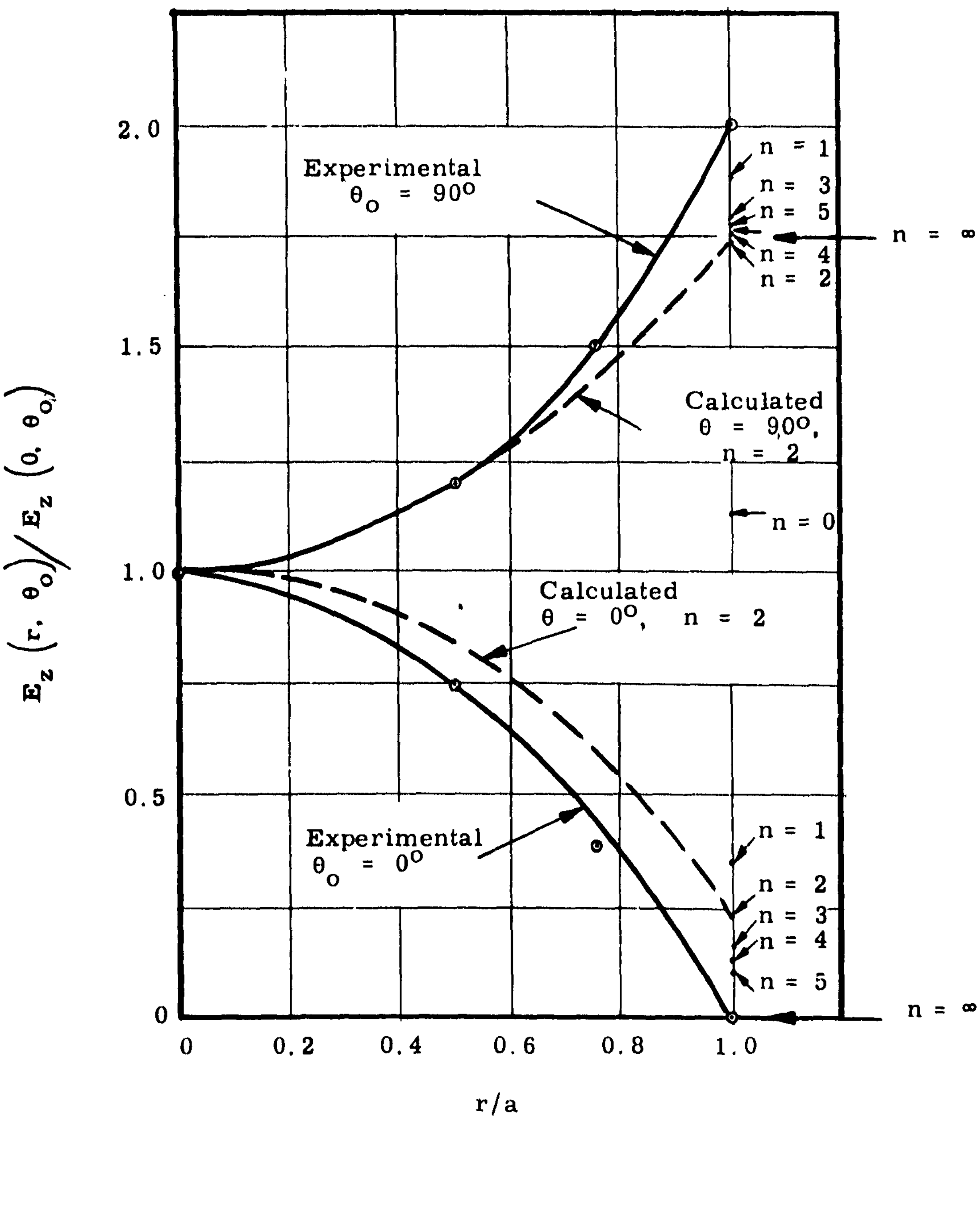


Fig. 4. Normalized E_z-field distribution for prototype as a function of radius for two cross sections for γa_i = 0.71.

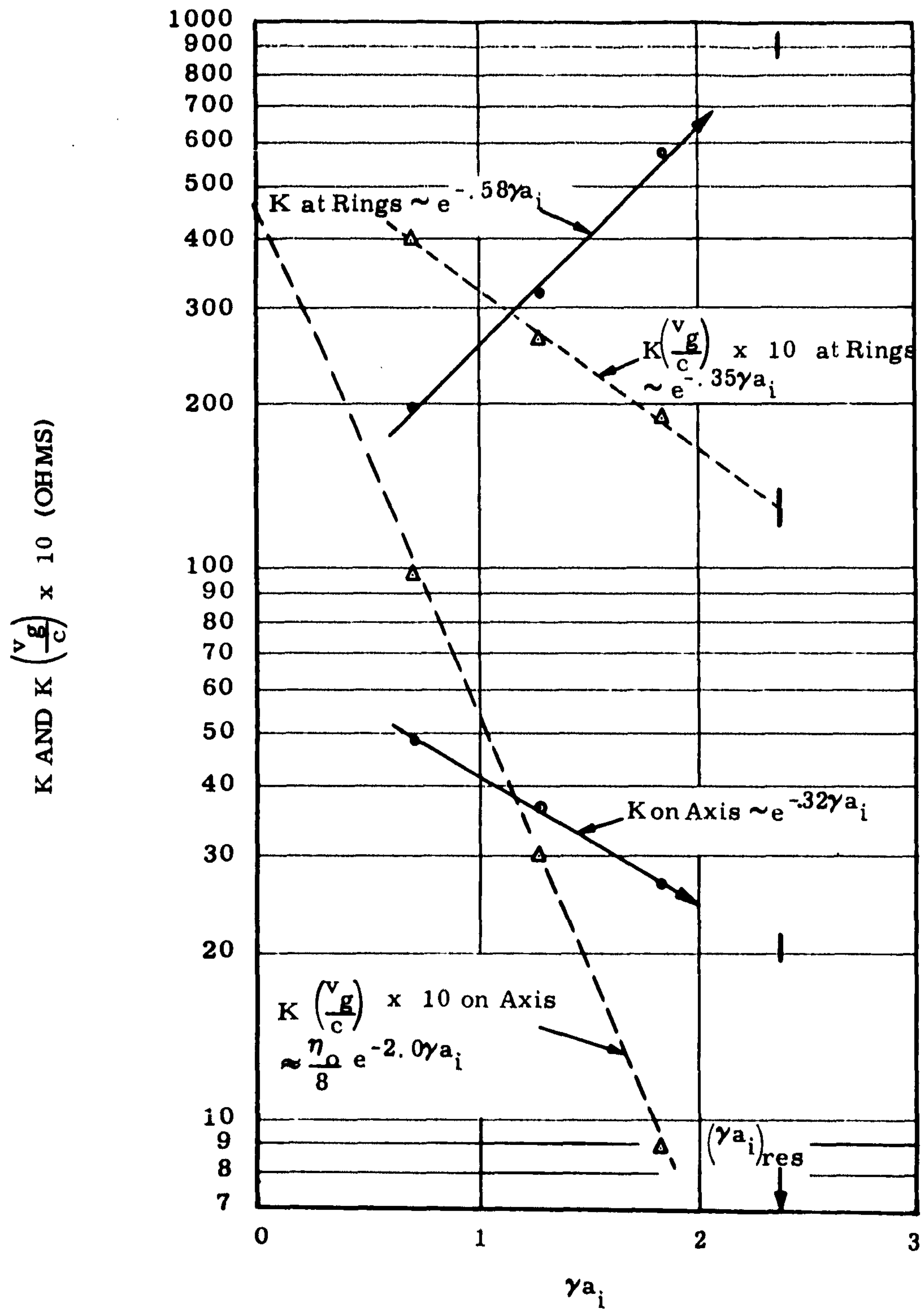


Fig. 5. Interaction impedance for ++ mode of the prototype circuit. Values are inferred from measured frequency perturbations. The arrows indicate the curve will continue to the resonance point (the short bar) but will be infinite at this point.

circuit with forced sinusoidal fields. If one chooses $E_z \sim I_o(\gamma r)$ for $r < a$, and $E_z \sim K_o(\gamma r)$ for $r > a$, the resulting impedance is an expression given in terms of Bessel functions, well represented by

$$K_{axis}\left(\frac{v_g}{c}\right) \sim \frac{1}{2}\left(\frac{\mu_o}{\epsilon_o}\right)^{1/2} \exp\left(-2\gamma a_i\right)$$

In Fig. 5 one sees the same γa_i dependence, but with a magnitude one-quarter that of the ideal circuit. This diminution is believed due to an unrealistic choice of "ideal" fields (several azimuthal harmonic terms, as given in Eq. (4), should have been used), but <u>not</u> due to ignoring axial spatial harmonics.

It might be mentioned that the +- mode can be analyzed similarly beginning with a series

$$E_T(r, \theta, z) = \sum_{n=\infty}^{\infty} \sum_{n=1}^{\infty} B_{m,n} I_n(\gamma_m r) \sin(n\theta) \exp j\left(\omega t - \beta_o z - \frac{2\pi m z}{p}\right) \quad (5)$$

and using the field dependence $E_z(a, \theta) = E_{zo}\left(a, \frac{\pi}{2}\right) \sin\theta$ as shown by the measured distributions for the +- mode in Fig. 3. The +- mode impedance is plotted in Fig. 6; values lie typically a factor of three below those for the ++ mode at a given γa.

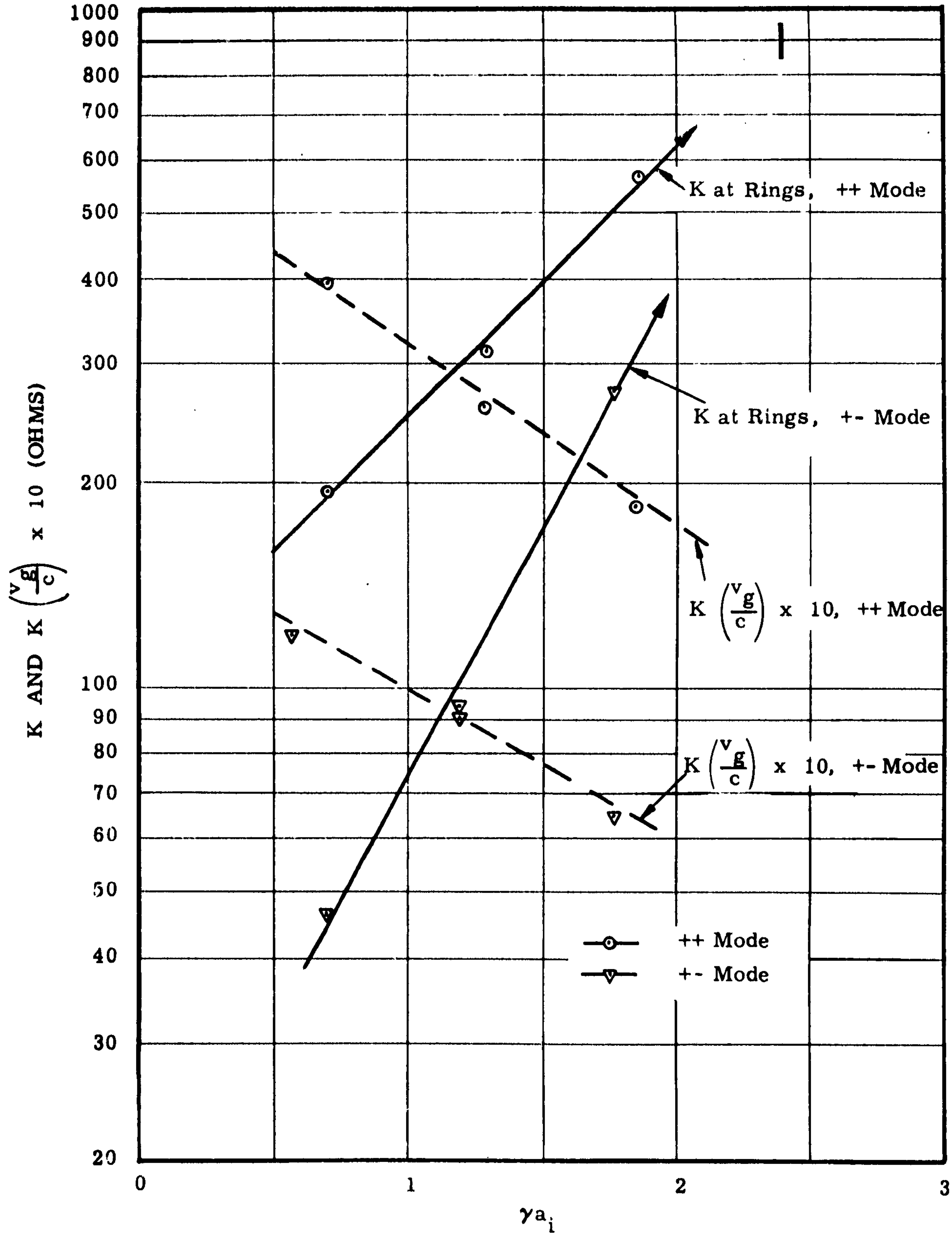


Fig. 6. Interaction impedance for +- mode of the prototype circuit.

EXPERIMENTAL TUBE DESIGN AND EVALUATION

Based on the information developed in the early phases of the program, a tube was designed and built to test one of these circuits. It was designed to operate at a frequency of 35 Gc, with a small signal gain of about 20 db. The work required to build such a tube included:

1. selection of the circuit,
2. development of circuit fabrication methods,
3. design of couplers (to couple both the ++ and the +- modes, to avoid internal loss),
4. design and test of windows, and
5. design and construction of electron gun.

Because of the field variation, two guns were actually built—one to produce a solid beam and the other to produce a hollow beam—so that by comparing results of the two guns the field variation with radius could be checked experimentally.

CIRCUIT DESIGN

The circuit chosen for use in the experimental tube was a scaled version of the prototype circuit shown in Fig. 2. All parameters were scaled by the same amount except for the pitch; which was scaled by a factor twice as large. The effect of this pitch change on propagation characteristics can be seen in Fig. 7. There were two reasons for decreasing the pitch of this circuit. First, it brings the ++ and +- modes closer together in frequency so that they can propagate through the same window; the bandwidth of the window is determined by this frequency separation. Second, when this circuit is used with an 80 kv electric beam, it interacts with all the modes with a positive phase velocity, thus eliminating the possibility of any backward-wave oscillations. The only oscillations that can occur will then require reflection somewhere along the circuit or at the output end of the tube. Thus, if the circuit is made with sufficient care and the couplers and windows are well matched, any forward-wave oscillations can be controlled external to the tube by proper matching.

Fig. 8 shows the circuit which was used in the experimental tube. The external shape of the circuit was machined from a solid piece of molybdenum, to produce

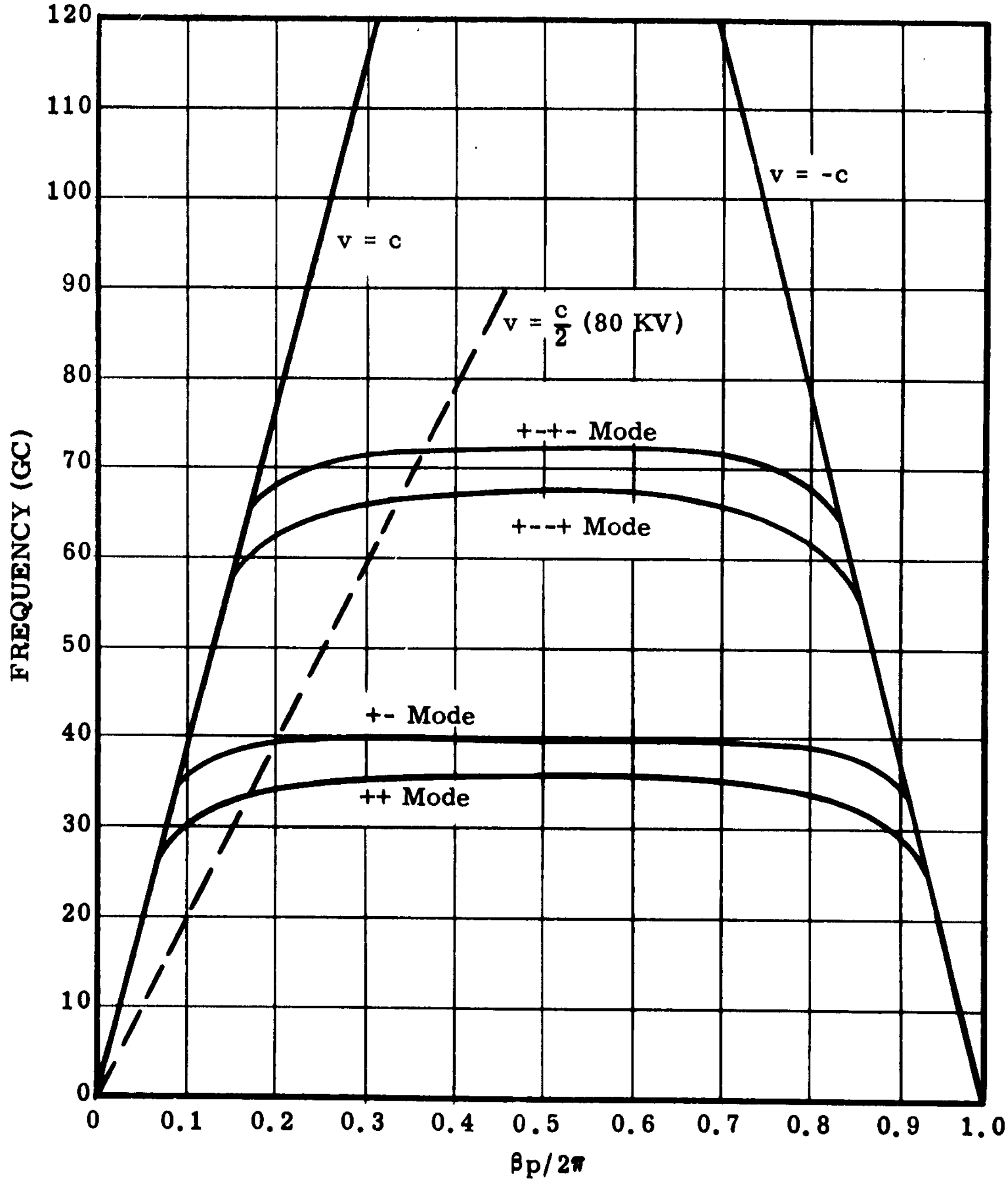


Fig. 7. Propagation characteristics for circuit used in tube. Dimensions are $p = 0.030''$, $\delta/p = 1/2$, $2a_i = 0.096''$, $2a_o = 0.125''$, $t = 0.015''$.

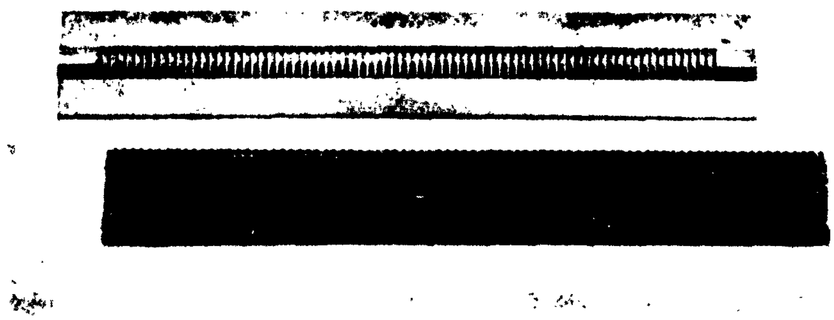


Fig. 8. Circuit, before plating, used in experimental tube.

a tube with planes attached. Then the rings were formed by a spark erosion machine. The circuit was copper plated before final assembly in the barrel and tube.

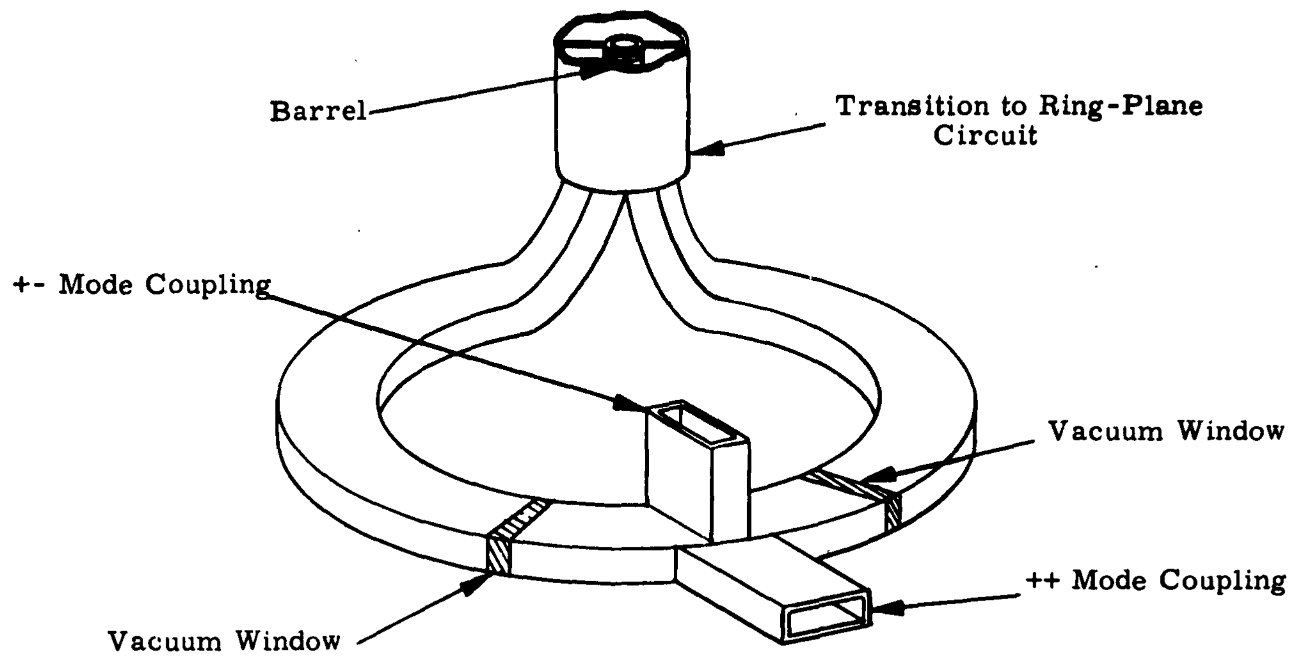
COUPLER DESIGN

A coupler was designed to match both the ++ and +- modes so that the match could be controlled external to the tube, thus eliminating the need for any internal loss along the circuit to control oscillations. A schematic of this coupler is shown at the top of Fig. 9. The lower portion of Fig. 9 shows, before final machining and assembly, the actual coupler used in the tube. In this coupler the energy from each side of the plane in the ring-plane circuit is coupled independently into two waveguides, which are then connected to a magic "T". The energy in the ++ mode on the circuit is in phase on opposite sides of the plane; when recombined in the magic "T" it will come out the H arm as indicated in the schematic. The energy in the +- mode is out of phase on either side of the plane; it is then recombined in the magic "T" and comes out the H arm. The input and output couplers are identical. Using this coupler, the two modes are essentially isolated by about 40 db from each other by the magic "T". Thus tests can be made on one mode by matching out the other mode to eliminate any oscillations or interaction in that mode.

The vacuum windows used before the magic "T" are ceramic windows one-half wavelength long, which are broadbanded by placing matching irises on either side of the window. The matches for the couplers and the windows are shown in Fig. 10. The matches shown here are without the magic "T"—that is, just the match of the transition from the waveguides to the circuit, and the window match. The match for the tube itself would be a combination of these two matches plus the match of the magic "T".

ELECTRON GUNS

Two electron guns were built. One produces a hollow beam and the other a solid beam. By testing the tube with both guns, the interaction with both modes can be checked with the two different beam shapes. As indicated by the radial field variation in the previous section, the interaction of the ++ mode for the two different beams should be quite similar, even though the circuit has a



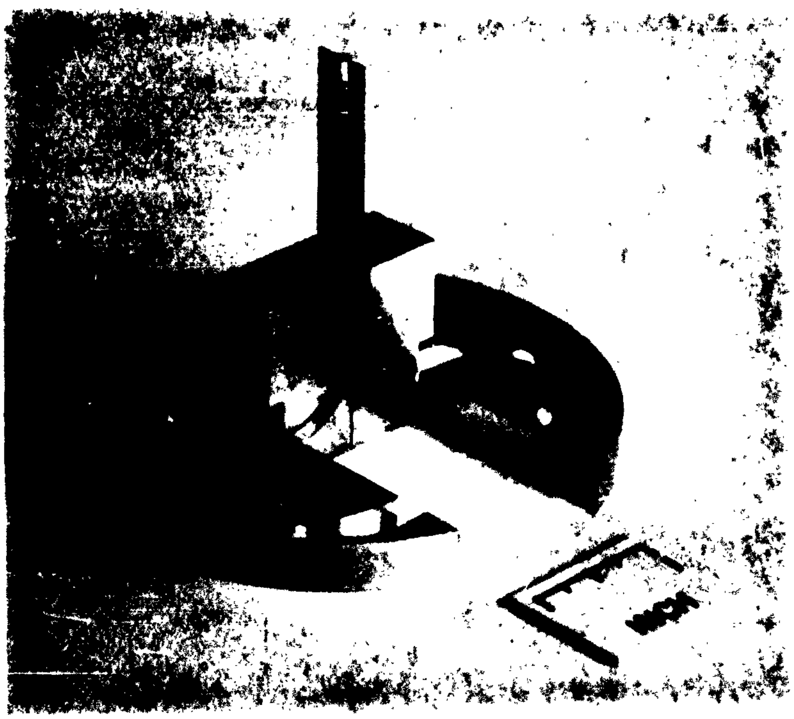


Fig. 9. Schematic of coupler used in test tube, and photograph of partially completed coupler.

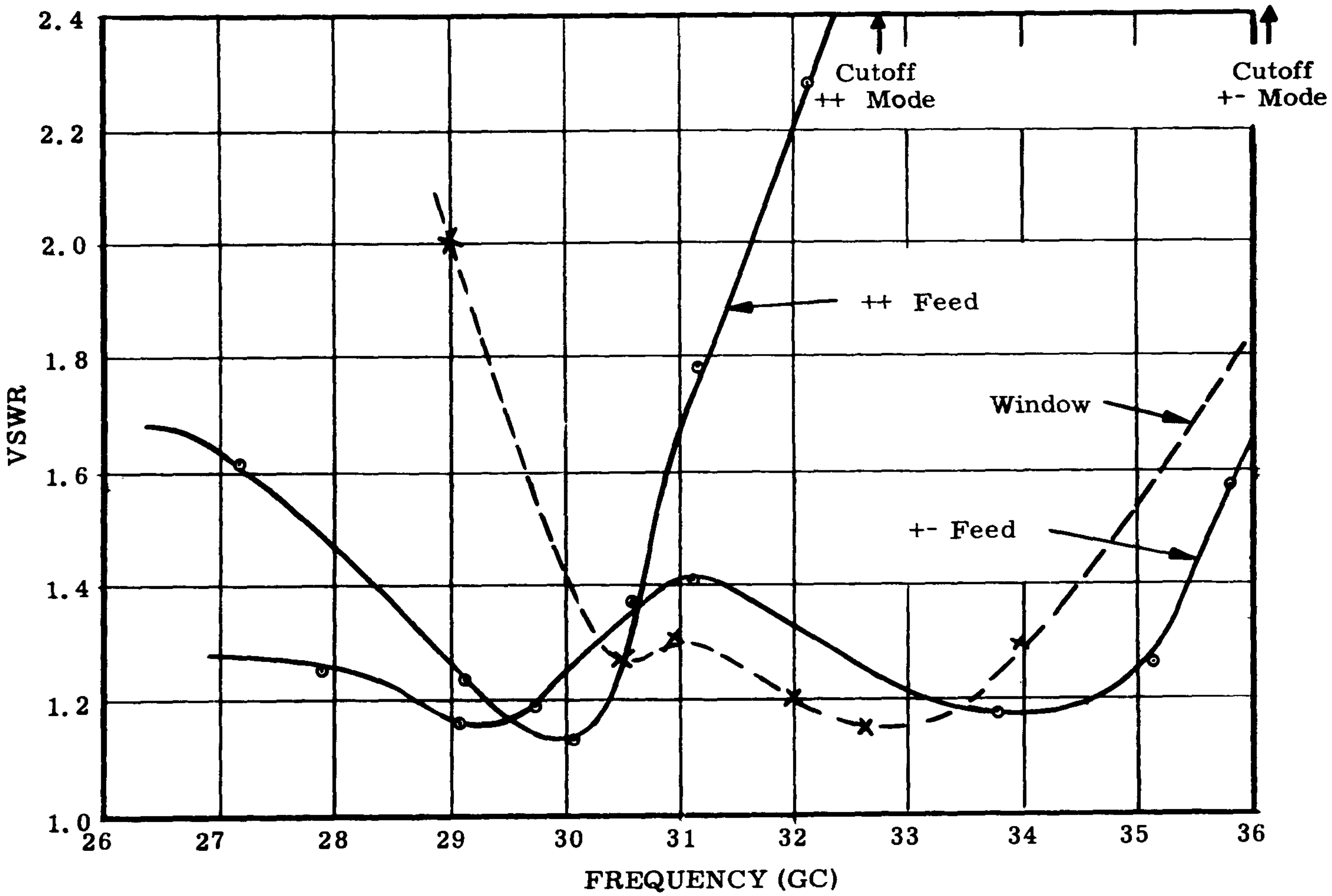


Fig. 10. Match of transition from waveguides to R-P circuit and broadbanded 1/2 wave-length window.

large ka or large cross section. The interaction with the +- mode should be considerably different for the two beams because of the rapid variation of the field radius for this mode.

The solid beam is produced by a conventional Pierce gun operating in a perveance of 0.06×10^{-6}. The beam is about 60 mils in diameter. Fig. 11 is a photograph of the gun. Fig. 12 shows the profile of the solid beam at various distances from the anode hole.

The gun which produces the hollow beam is the magnetron injection gun, and has a unique feature. Magnetron injection guns normally operate at high perveance. Because operation here is at low perveance, a modulating anode was placed in the gun so that the perveance can be varied. A schematic of this gun is shown in Fig. 13. In the region between the cathode and the modulating anode, the gun operates as the usual magnetron injection gun with the high perveance. Then, once the electrons start to move toward this anode, the magnetic field forces them into the region where they are controlled by the regular anode. This produces a hollow beam at low perveance where the perveance is variable. In this gun, the perveance was variable from about 0 to 0.1×10^{-6}. The actual gun is shown in Fig. 14, mounted on a beam tester for high-voltage testing; the beam that is produced is shown in the upper left corner.

EXPERIMENTAL TEST RESULTS

The experimental tube was built, using the circuit couplers, windows, and guns described in the preceeding sections. It has the following parameters.

Beam voltage	80 kv
Beam perveance	0.06×10^{-6}
Frequency (++)	33 Gc
Gain (++)	20 db
Frequency (+-)	35 Gc
Gain (+-)	6 db
Length of circuit	1.8 inches
ka (++)	0.762
Beam diameter to circuit diameter	0.64

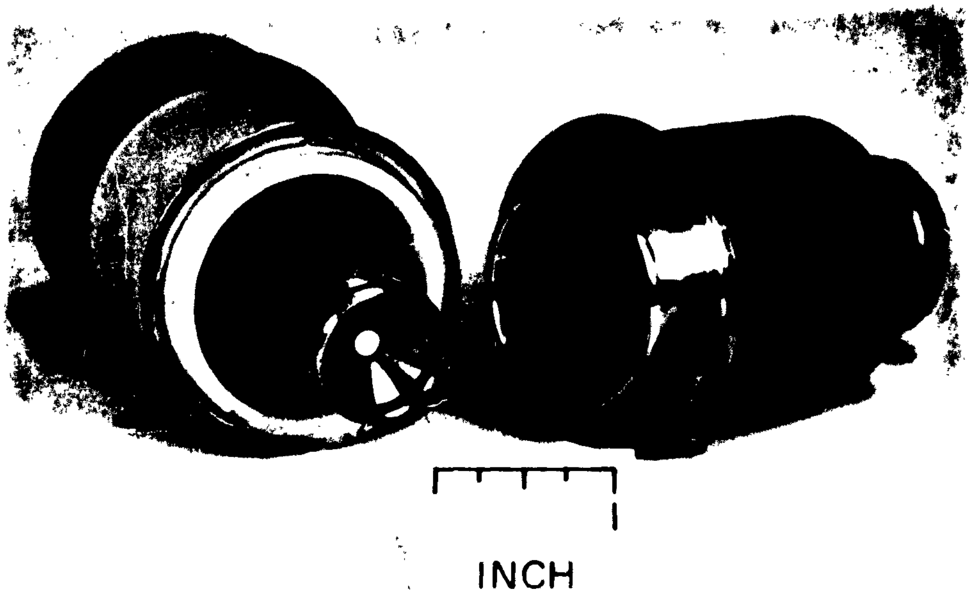


Fig. 11. Electron gun used to produce solid beam.

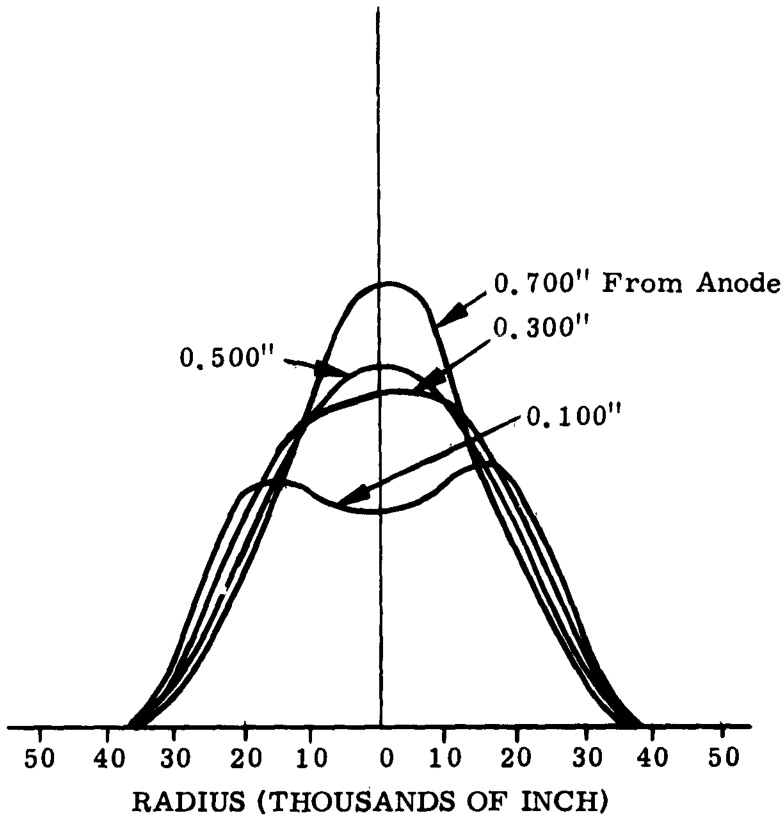


Fig. 12. Profile of solid beam at various distances from anode.

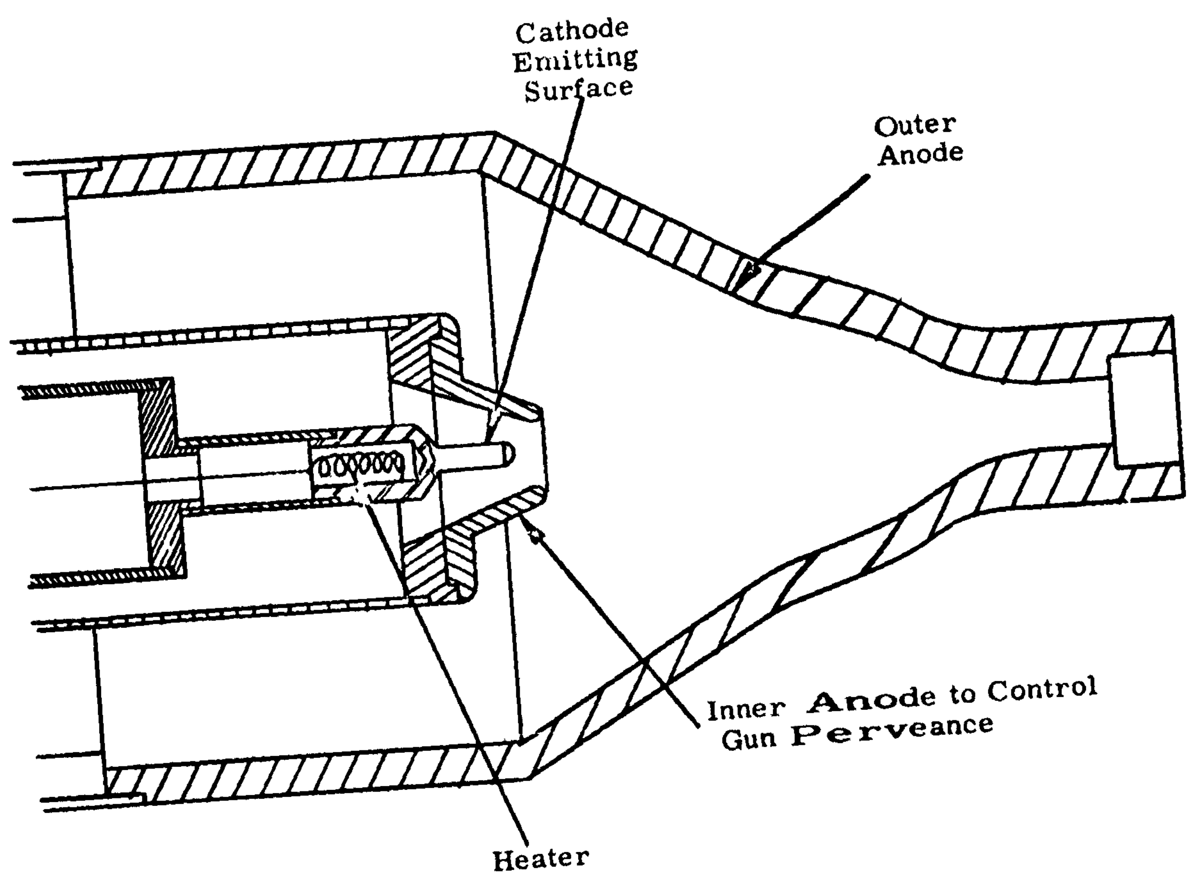
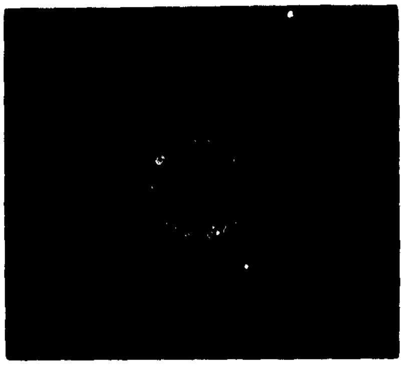


Fig. 13. Magnetron injection gun with electronically variable perveance.



ID = 0.040 inch
OD = 0.060 inch

Fig. 14. Beam produced by magnetron injection gun (upper left) and gun mounted on a beam tester for tests.

With these parameters, the beam has about 100 kw of peak power at a duty factor of 10^{-4}. One would expect, for this circuit and beam, an efficiency of about 2 C or about 10 per cent, and peak r-f power of 10 kw. It should be noted here that this is a fairly modest beam, since the circuit is capable of handling much higher powers. Calculations show that this circuit should be able to handle 200 watts on a continuous basis. Thus with a transmission of 90 per cent, output powers of 2 kw CW could be obtained. Clearly the present beam does not represent the ultimate capability of this tube. It is entirely possible to increase the perveance of the beam, thereby increasing the power and producing a corresponding increase in efficiency and gain.

The assembled tube is shown in Fig. 15. The four waveguides are shown on the input and output couplers for the two separate modes. This tube was tested with respect to gain, saturated power out, and bandwidth.

The gain of the tube with the solid beam is shown in Fig. 16. The gain at 33 Gc (++ mode) is very close to the 20 db expected, and follows the theoretical gain curve fairly well. The experimental gain shown for the +- mode runs about 3 db. The theoretical gain for this mode was calculated to be about 2 to 6 db, depending on the beam radius. Thus, unless the exact beam diameter is known, there can be a fairly large discrepancy in the predicted gain for this mode. The experimental results fall within the lower end of this range.

Power and efficiency of the ++ mode are shown in Fig. 17. As can be seen, the maximum power obtained was about 15 kw. This corresponds to an efficiency of about 10 per cent, which is quite close to 2 C. At the higher frequencies the efficiency drops to about 3 per cent. It should be noted here that the variation in efficiency is fairly small. This tube could, therefore, be used quite successfully as a voltage-controlled variable power oscillator if the slight frequency change can be tolerated. The gain power obtained for the +- mode was also checked at a number of points; the variation for the two beams, at 36.2 Gc is shown below.

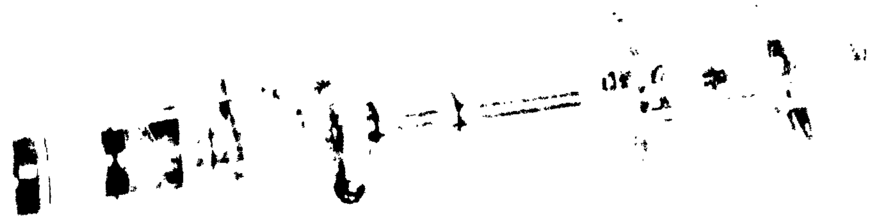


Fig. 15. Experimental tube fitted with solid beam gun and waveguide.

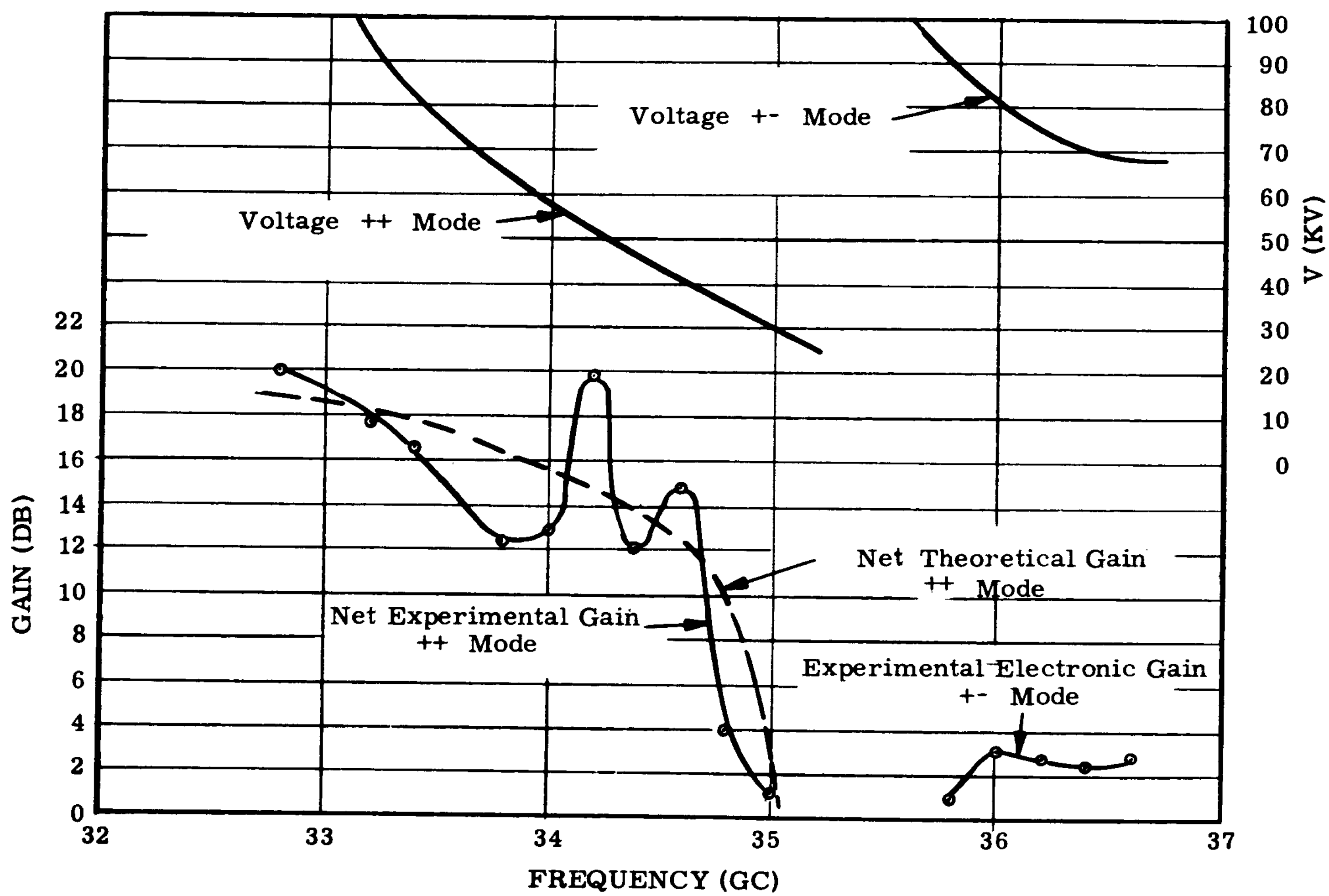


Fig. 16.. Gain of experimental tube using the solid beam.

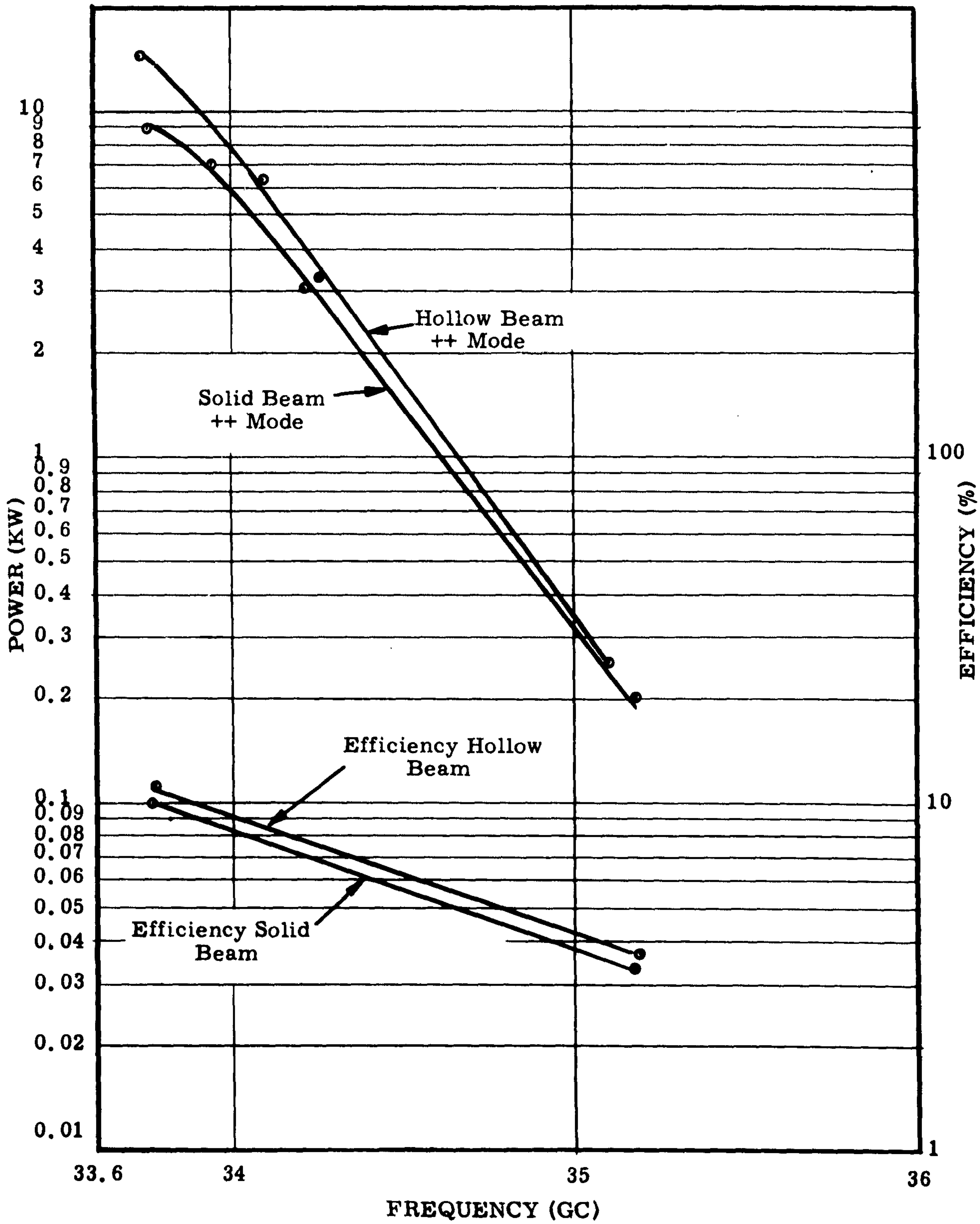


Fig. 17. Power and efficiency versus frequency for hollow and solid beam, ++ mode.

	Oscillator Power (KW)	Efficiency (%)
Solid beam	0.5	0.5
Hollow beam	4	2.5

Here it can be seen that the difference between the two beams is quite marked, as one would expect, because of the radial field variation.

The operating bandwidth of the tube was also measured by fixing the voltage and then measuring the gain as a function of frequency. The measured values were about 1/2 per cent bandwidth between 3 db points. The predicted bandwidth for this circuit is about 1 per cent. It is noted that, as was stated in the Third Quarterly, this does not represent an ultimate capability bandwidth for this tube. With this same beam this circuit can be modified to give about 14 per cent bandwidth and the bandwidth could be increased even further by using a higher perveance beam so that bandwidths in the order of 20 to 25 per cent would not be unreasonable with these circuits.

CONCLUSIONS

The conclusions that can be drawn from the study program and the experimental verification with the operating tube are as follows.

1. The ring plane circuits are very well suited to the high frequency region due to their large size, operation is feasible with a solid beam or hollow beam operating with a ka of about 1, and the study program indicates that operation with a ka around 2 with the higher modes may be possible.
2. The ring plane circuits have excellent high power capabilities due to the good cooling provided through the planes of the circuit.
3. The circuits can be operated either as amplifiers or as oscillators by proper choice of the circuit. That is, the circuit can be chosen to interact with either the forward wave or the backward wave components of the circuit.
4. The circuit is capable of bandwidths in excess of 10 per cent with the proper choice of beam, and the circuit bandwidths up to 25 per cent would not be unrealistic.
5. The circuit has fairly high impedance, indicating a strong interaction with an electron beam to obtain high impedances and efficiencies.

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AF Avionics Laboratory,
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Rpt Nr ASD-TDR-63-569
APPLIED RESEARCH OF BEAM INTERACTION STRUCTURES FOR TRAVELING WAVE TUBES
Final Rpt, May 63, 28 p. incl. 17 illus.

Unclassified Report

Study program was conducted, and experimental tube built and tested. Two possible modes were coupled independently through separate waveguides. Tube tested with both hollow and solid beams. Gain 20 db in ++ mode, ~ 3 db in +- mode. Power in ++ mode ~ 15 kw with hollow beam, ~ 8 kw with solid beam, representing efficiencies ~ 10%. Power in +- mode 4 kw maximum with hollow beam, ~ 0.5 kw maximum with solid beam. Tube is basically an amplifier; part of output power was fed back to input for power measurements.

These ring-plane circuits are very well suited to high-frequency, high-power region as both oscillator and amplifier. They can have high gains and high efficiencies with large peak and average power capabilities.

1. Traveling-wave tubes
2. Electron tubes
3. Slow-wave circuits

I. ASD Proj. 4156, Task 415603
II. Contract AF 33(657)-8360
III. General Electric Company, Palo Alto California
IV. C. E. Enderby
V. Secondary Rpt No. TIS-R63ELM233-5
VI. Aval. fr OTS
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